APPLIED HYDRAULICS AND HYDRAULIC INSTRUMENTATION

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Summary

The broad spectrum of flow measurement for various purposes in free-surface and closed conduit hydraulic systems is covered, with reference to the measuring techniques and instrumentation developed in the course of time. The measurement of the relevant flow properties that include stage or level, discharge or flow, velocity and pressure, bed and suspended load transport, and other fluid and flow parameters, such as density, temperature and turbulence, is discussed. The importance of data transmission and storage, both for being readily available at short notice, as well as for reliable future reference purposes, is emphasized. Automatic control and standards of flow measurements, are also dealt with briefly. More detailed treatments are described in the topic articles that follow.

1. Introduction

In the Theme article on *Hydraulic Structures and Equipment and Water Data Acquisition Systems* hydraulic instrumentation is mentioned several times. Gathering data about the flow of water has for centuries been, is today, and will in future be essential for humankind, as water is both a necessity for life and a tremendous hazard when uncontrolled. Sustainable use of water, and viable protection against water hazards, are only realizable with sufficient knowledge about the behavior of the water.

The fundamental understanding of the physical behavior of water is described in the topic level articles of the leading topic (see *Fluid Mechanics*), of this Theme (see *Fluids at Rest and in Motion*).

By using adequate methods of modeling flow behavior, it becomes possible for humankind to change the natural flow of water and use it for different purposes, as dealt with in the topic level article for the following topic (see *Hydraulics*), of this Theme (see *Hydraulic Methods and Modeling*). How to utilize water, and also how to reduce the adverse impact of excess water on living conditions, are described in the topic (see *Water Resources Development*), which follows the present topic (*Applied Hydraulics, Flow Measurement and Control*).

The missing links between these three fields described above are addressed in this topic, namely, the determination of the flow at the place where it should be of influence, and some basic techniques to manipulate or control that flow. This is the actual topic to be addressed here, and this introductory topic writing describes the related subjects by linking them to these basic needs. Some basic ideas are described, and special attention is given to recent developments, as well as to outlining possible developments in the future.

Trying to systematize the diverging views on hydraulic instrumentation, for serving the various purposes elaborated above, makes it necessary to ask certain relevant questions before carrying out any measurements: "In what kind of hydraulic system should measurements be taken?"; "What should be measured?"; "At which place should measurements be taken?"; and "For what purpose are the measurements needed?" All these questions are strongly coupled to each other. However, the reason for the measurement has to be identified at the outset. With this basic information the answer to the question "What should be measured?" can be tackled, if the hydraulic system is known.

Although some specific facts are described here, the hydraulic systems themselves are not discussed in detail, but are dealt with later in the various articles under this topic. These articles that follow the present one explain what is done under special circumstances, such as in the cases summarized below:

- Maintenance of Flow Channels. One of the most challenging fields in applied hydraulics is the maintenance of flow channels in rivers and estuaries for navigation purposes. Various types of dredging equipment and vessels specially designed for this purpose have been developed over the past centuries. Sophisticated forms of control, guidance and measuring equipment have been devised. A thorough description of these interesting technological innovations in this challenging field, coping with the ever-increasing demands by shipping enterprises, is found in the first article in this topic (see *Dredging Technology*).

- Flow Measurement. A fundamental understanding of the properties of flow and the parameters of flow measurement is necessary for the practicing hydraulic engineer. Not only the instrumentation developed for this purpose, but also the reliability of the measurements, and the availability of measured data, in both the short term and the long term context, is of cardinal importance. The second article in this topic deals with the fundamentals of flow measurement, its accuracy, error estimation, data transmission and recording. This forms the basis for the next two topic articles dealing with the more specific cases (see *Flow Measuring Techniques*).

- Closed-Conduit Flow Measurement. Water suitable for consumption is generally conveyed under pressure in closed conduits, such as tunnels, pipelines, distribution networks, penstocks, well-casings and pumping station manifolds. The measurement of the flow rate of water through conduits is generally done by *in-situ* flow meters. The article describes both the indirect flow measuring systems based on pressure differentials through constrictions in the conduit, as well as the direct measurement systems, such as ultrasonic, electromagnetic, and laser-Doppler techniques. The choice, suitability and application of flow metering instruments for various purposes are also described (see *Flow Measurement in Closed Conduits*).

- Free-Surface Flow Measurement. Bulk water supply from rivers and underground water sources, has to be measured and monitored for quantity control purposes. Such water is volumetrically measured by stage level observations in reservoirs, or piezometric measurements of groundwater levels. The flow of water can be measured more accurately when conveyed in a channel of constant cross-section, or when passing over a hydraulic weir designed for this purpose. By measuring velocity in the first instance and water head, or stage, in the second case, and applying a so-called rating curve, accurate determinations of discharge is possible. Rivers and streams may also be gauged *in-situ* by means of current meters suspended from cableways or mounted on overhead supports. The article covers the various free-surface flow measuring systems (see *Measurement of Free-surface Flow*).

- Hydraulic Flow Control Systems. In applied hydraulics, a cardinal aspect is the reliable control of water in storage, its programmed release and distribution to the user. To effect this to a satisfactory degree, some very sophisticated control devices and systems have been developed over the past century. The basic principles of control and the techniques and instrumentation required in practice are discussed in an article that addresses the main issues (see *Control Systems for Hydraulic Structures and Equipment*).

- Water Conveyance Systems and Flood Control. In the final article in this topic, a number of examples of applied hydraulics as found in the various methods of conveying water from source to consumer, are dealt with. These conveyances are generally free-surface conduits, such as canals, flumes, etc., for bulk water supply. For treated water, where quality has to be maintained and losses minimized, use is made of closed conduits, such as tunnels or pipelines. Apart from the supply of water, it is also necessary to exercise some form of control over used water that has to be disposed of in the form of effluent. The remaining consideration involves the design and operation of hydraulic structures and devices to manage floods. These three fields, involving various types of control equipment, are dealt with in the final article in this topic (see *Water Conveyance Systems and Flood Control Works*).

2. Stage Measurement

Water heights related to a certain datum, or level above an arbitrary reference plane, are known as stage levels. It could be the stage above mean sea level, or the stage above the local river bed level. It is necessary to measure, as well as predict, what the water stage would be at various points along the course of a stream, river, floodplain, estuary or near shore region. For this reason, stage measurements, or alternatively water depth measurements, need to be made during flow conditions. Similarly, it is also needed to know what the bed elevation is below a certain datum plane—for example, in piloting ships along confined waterways, the depth below the mean lowest low water level is of the utmost importance. Stages or water depths, therefore, have to be measured, and also predicted.

2.1. Need for Water Depth Measurement

As rivers and lakes form the most important natural interactions of water with humankind, the reasons for stage measurements should first be given for such types of free-surface flows as are associated with natural water courses.

The most important and certainly the oldest question asked about a free-surface flow is: “How deep is the water?” and at least some of the reasons why this query is made are widely known. The possibility of crossing a river or stream on foot or by car is limited, if a certain safe water depth is exceeded. The possibility that a ship can use a certain river is limited by the need for the water to be at least as deep as the ship draws in the water.

The first requirement above makes it necessary to find the deepest place along the path across a flow channel or flume, and measure the depth. A stick of known length can be a measuring device well suited to this situation. The second requirement is much more demanding as, in principle, the depth all along the course of the ship’s route must be measured. The technology for obtaining this information was for centuries the use of a plummet (sounding lead) thrown into the water from the bow of the ship; nowadays this has been replaced by an echo sounder that continuously signals the distance to the sea bottom for an area surrounding the ship (see ISO 4366).

In all the above-mentioned cases, instantaneous measurements are taken as required. The reason, therefore, is that the bottom of a river continually changes. However, if the riverbed is fixed or maintained in a way that a certain level of the bed is maintained regularly, it becomes possible to avoid these continual measurements by replacing them with:

- measuring the depth of the river with respect to a specific locality only once;
- the repetitive measurement of the water level at that specific locality; and
- distributing the information of a guaranteed minimum water depth in the river to the various users, such as ships, barges, etc. (see *Dredging Technology*, and *Dredging in Rivers and Estuaries*).

In comparison with the method using the plummet or echo sounder, the advantage of this new system is that the information is available before reaching a locality, and thus the travel route can be planned ahead. As the fixed costs of ships are very high, they should be *en route* almost every day, and they should load as much cargo as possible (getting a large immersion depth in this way). Thus, obtaining the valuable kind of data explained above is of very great economic importance, and is needed frequently. This example thus depicts the value that basic hydrological data measured worldwide at many rivers and lakes can have.

2.2. Need for Water Level Measurement

The question: "How high is the water (level)?," corresponding to the previous question on water depth is also very common, as the flooding of an area surrounding a river can be both a benefit (the wetting and desalination of agricultural fields), as well as a detriment (flooding of living and industrial areas, flooding of fields during the growth of the crops). Measurements in answer to this question were already performed in ancient times—especially, measurements made on the river Nile are known to have been done for about five thousand years.

With this in mind, it becomes clear that the storage of measured data is as valuable as the measurements themselves. It is only with access to the historical data (stored results of former measurements) that it becomes possible to interpret the data measured at the present time. A conclusion such as: "This year the maximum water level is as low as twenty-five years ago, and at this low water level about 90% of the crops withered," may be essential for ensuring the survival of human beings, e.g., by importing food.

This is the second reason for the determination of the water level in a river, and it is now performed at almost all larger rivers. It should be pointed out that, in spite of the importance of knowing what the water level in an open channel itself is; this information is also needed as input for many other flow-related hydraulic measurements (as mentioned later). Hence, it is also necessary to gauge the water level during free-surface flow, in connection with almost all the other measurements which have to be done (velocity, discharge, etc.).

2.3. Performing Water Level Measurement

For both the questions mentioned above, it is useful to monitor the water level in relation to a certain pre-determined altitude and calculate the required water stage values from a known profile (of the riverbed, the surroundings etc.). A lot of effort has gone into developing systems suitable for different kinds of stage measurements (see *Surface Water Data Acquisition*).

Further references can be made to the codes applicable in different countries (e.g., DIN 19559 in Germany) or published by international organizations (see ISO 4373 and ISO/TR 11330). The "Pegelvorschrift" (a manual for water level gauging and discharge measurements) developed by the German Federal Hydraulics Working Group (Länderarbeitsgemeinschaft Wasser, LAWA) has found worldwide application, although the specific rules were originally mainly developed for conditions in Germany. Its detailed procedural breakdown has resulted in widespread use.

2.4. Changing the Water Level or the Water Depth

Finally, it should be pointed out that water levels are normally not stationary as nature is never static, but always changing with time. The water level in a lake, for example, depends on the volume of water in the lake (and is affected by the inflow and the outflow). The water level in a river depends on the volumetric rate of flow that is passing a certain section of the river (this is known as the discharge).

Furthermore, the force of the flowing water is always likely to be changing the bed of the river, the particles of the riverbed will be moved away, and other particles will again be deposited under certain circumstances. Based on the physical behavior and related models, it becomes possible to predict the future development of a riverbed, if some data about its past behavior exists. Such data can be measured and collected, taking into account the needs at the place investigated, and the technical remedial possibilities.

It might be possible to change the water regime to obtain enough depth to be able to use the channel for ship transport (as discussed in the earlier example). Two basic principles can be applied: dredging the riverbed or damming up the water. Both are described in detail in later articles (see *Dredging Technology*; *Large Dams*).

3. Discharge Measurements

Measurement of the discharge or volume rate of flow is important for various reasons. It may be needed for hydrological data, or for water supply assessment, to know the exact rate of yield of a river or stream. Discharge is a rate of flow that varies constantly from place to place, and in time, for any particular river reach. It is not directly measurable, but can be assessed by means of indirect measurements, as will be described below.

3.1. Need for Discharge Measurement

A third question generally asked about free-surface flow is: "How much water is flowing?" One very important reason for this question is that the water level depends on the rate of water flowing in the river. It is, as discussed later, possible to formulate a relationship between discharge and water level (i.e., stage), which allows for the prediction of a water level from a known discharge value at a certain location upstream. With this, it is possible for human beings to react to a rising water level before a certain critical value is reached. It also becomes possible to protect cities by constructing temporary flood control dams, or to implement emergency measures to reduce the impact of flooding, such as by moving expensive equipment from cellars, and so on (see *Water Conveyance Systems and Flood Control Measures*).

A second reason for asking the question on how much water is flowing, which perhaps dates back further in time, is that water is an extremely valuable commodity that could be sold or purchased at a price. In ancient cultures, the water used to irrigate the fields was scarce, and was sold by measurement of quantities (for example in acre-feet, centimeters water application depth, cubic meters, etc.). Some of these volumetric quantity measurements are still being used. But new reasons have also been developing; for example, the quantity of polluted water that is often allowed to be released into a river usually depends on the discharge of the river itself. For several reasons therefore, the discharge must be measured. How this is done will be dealt with next.

3.2. Direct Discharge Measurement

Measuring discharge directly would be ideal, if possible. This can be done for a stream or river where it connects with a storage reservoir where the stage and hence the volume change can be determined over a certain time period. This would yield the average discharge over that period. Instantaneous direct measurement of discharge in a natural water course is not readily possible, and then it is necessary to resort to indirect measurement.

3.2.1 Direct Discharge Measurement by Collecting the Quantity of Water per Unit of Time

The easiest way of measuring discharge is by direct volumetric measurement. That implies directing the whole flow into an empty container and measuring the time needed to fill the container (see ISO 8316). The discharge of one container per period of time can easily be transferred to conventional units (i.e., cubic meters per second). Undoubtedly it is also possible to measure the quantity gathered in a graduated container over a predefined time. It is obvious that this methodology is only possible for very small streams or flumes built to irrigate crops. This is impossible with actual rivers under normal flow conditions, and indirect methods, therefore, have to be used.

Other kinds of direct discharge measurements do exist, but they are limited to certain cases, and are not very easy to apply (for instance measuring average velocity over a constant cross-section in closed conduit). In rivers, the stage varies with the discharge, and therefore, the cross-section also varies, which is then not directly determinable.

3.2.2 Inductive Discharge Measurement (IDM)

One method of direct discharge measurement makes use of the electrical conductivity of water. If water crosses an electric field, it influences the field depending on the amount of water crossing the field per unit of time. This distortion of the field can be measured, and as the relation is very clear, the discharge can be determined exactly. But solving this relation requires that the field that is influenced is very stable and uniform. The creation of such an electrical field is quite easy. If a metallic tube surrounds the flow, it protects the inside electric field from outside influences. Furthermore, the tube can be used to distribute the electric field more evenly in the flow. This is the basis for a very exact and common method of measuring flow in pipelines, ISO 6817, ISO 9104, ISO 13359 (see *Flow Measurement in Closed Conduits*).

Therefore, the most precise way to measure the flow in a river might be to let it pass through such a tube. But then the river is not a river anymore, and consequently this is not feasible, mainly for environmental reasons. However, for industrial applications (channels for wastewater treatment, for example) this is a solution that is often applied. For some smaller flumes, installations with a metallic sheet beneath the bed were tried, but disturbing influences from the environment were found to be too strong for successful measurement.

3.2.3 Direct Velocity-Integrating Discharge Measurement (VISAB)

Another method of direct discharge measurement is the release of air bubbles along a line, such as a hose crossing the river on the riverbed. If these air bubbles have a certain size, they will move to the surface with a specific velocity that is nearly constant. That means that they will traverse every vertical unit-depth of the river's cross-section in the same time interval. The movement of the water will shift them downstream. But due to the constant vertical velocity, the influence of every part of the river cross-section has the same weighting, and the resulting movement downstream depends only on the velocity of the water.

If it is possible to recognize the line of air bubbles at the surface, and determine the distance to the hose (which can be carried out by a video camera and image processing), the discharge can be calculated directly from these distances, the length of the river crossing, and the calculated velocity of the upward movement of the air bubbles. This is a very elegant development in the field of measurement described in the following section; it is the only method integrating all the differential velocities. It is only possible to sum up certain, hopefully representative, values of the methods of velocity measurement described next. Nevertheless, VISAB, as this method was called, is still under development and presently has some technical limitations.

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